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HEARING ON
CLIMATE CHANGE IMPACTS AND RESPONSES IN ISLAND COMMUNITIES

BEFORE THE
SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

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Introduction

Good morning Senator Inouye, members of the committee, ladies and gentlemen. Thank you for giving me the opportunity this morning to speak to you on global climate issues and how they might impact island communities. My name is Fred Mackenzie and I am an Emeritus Professor in the Department of Oceanography at the University of Hawaiʻi. My research is quite broad in scope but focuses on the behavior of the Earth's surface system of oceans, atmosphere, land, and sediments through geologic time and its future under the influence of humans, including the problems associated with greenhouse gas emissions to the atmosphere, global warming, and ocean acidification. I have been an academician for more than 45 years and published more than 250 scholarly publications, including six books and nine edited volumes in ocean, Earth and environmental science. Today you have asked me to comment on how climate change might affect island communities and on our recent work developing climate and sustainability case studies for Pacific island resources that can be used to educate and inform the community, including local decision makers.

Many of my comments are derived from the report of the Pacific Islands Regional Assessment Group, for which I served as a member, entitled *Preparing for a Changing Climate. The Potential Consequences of Climate Variability and Change* (Shea et al., 2001), and the case study *Climate Change, Water Resources, and Sustainability in the Pacific Basin: Emphasis on Oʻahu, Hawaiʻi and Majuro Atoll, Republic of the Marshall Islands* (Guidry and Mackenzie, 2006). I and my colleagues have used these materials and my books *Our Changing Planet: An Introduction to Earth System Science and Global Environmental Change* (Mackenzie, 2003) and *Carbon in the Geobiosphere—Earth's Outer Shell* (Mackenzie and Lerman, 2006) to educate the public and students at all levels in Hawaiʻi and elsewhere about climate change and its impacts. We also have run an immersion course for native Hawaiian students and a course for the Myron B. Thompson Charter School in Hawaiʻi employing these texts and an interactive web site as resource materials.

General Comments on Climate Change

The science of climate change has been assessed in a series of four reports by the Intergovernmental Panel on Climate Change (IPCC), a body of 2500 scientists that, as you are aware, shared the 2007 Nobel Peace Prize for their work on distilling the scientific community's research on the physical and biogeochemical basis for climate change into authoritative reports. Similar sized volumes on mitigation and impacts, adaptation and vulnerability have accompanied the more recent science volumes. The panel's latest 2007 physical science report *Climate Change 2007: The Physical Science Basis* (IPCC, 2007) includes a full chapter on regional climate projections that for temperature, precipitation, and extreme weather projections are very similar to the Third Assessment Report (TAR) of the IPCC in 2001, as are the global climate assessments and projections. The major difference between the TAR and the 2007 report is that generally the projections have a higher level of confidence due to a larger number of simulations, improved models, a better understanding of model deficiencies, and improved detailed analyses of the results. It should be kept in mind that the distillation of the science of climate change by the IPCC in their 2007 report only dealt with findings up until the year 2005. More recent findings from 2005-2007 studies are included in this testimony. Also it is still very difficult to take the information from the IPCC physical science report and use it to predict the future of regional and short-lived annual events, like day-long high sea levels and floods, or even inter-annual (El Nino/La Nina) or decadal (North Atlantic and Pacific Decadal Oscillations) climate changes and their effects on precipitation, sea level, and hurricane frequency or intensity.

At its most basic level, the balance between incoming solar radiation and outgoing infrared heat radiation determines Earth's climate. The absorption of the outgoing Earth radiation by atmospheric greenhouse gases of methane (CH_4), nitrous oxide (N_2O), and especially carbon dioxide (CO_2) and the consequent heating of the lower atmosphere are what constitute the well-recognized "greenhouse effect". It should be kept in mind that water vapor (H_2O) is the most potent greenhouse gas. The greenhouse gases have for most of planetary history resided in our atmosphere and by trapping outgoing Earth radiation have maintained the Earth at a temperature amenable to life. Thus, there has always been a greenhouse effect, but humans by adding greenhouse gases to the atmosphere are increasing the strength of the greenhouse effect. The Earth without greenhouse gases in the atmosphere would be -18 ^{o}C, 33 ^{o}C colder than the late pre-industrial global mean temperature of 15 ^{o}C. We have had an "enhanced greenhouse effect" operating since at least the beginning of the industrial era.

It is well known and documented that the greenhouse gases of carbon dioxide (CO_2), methane CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) have increased markedly in the atmosphere due to human activities. The global increase of atmospheric carbon dioxide from 1750 to 2007 has been about 36%, from 280 ppm (parts per million) to 382 ppm globally and 385 ppm at the Mauna Loa Observatory on the Big Island of Hawai'i. Atmospheric carbon dioxide levels are higher today than they have been in more than 600,000 years. The global increases in carbon dioxide concentration are mainly due to fossil fuel use and land use changes. The increases of methane from 715 to 1774 ppb (parts per billion) and nitrous oxide from 270 to 320 ppb are primarily due to agriculture. The concentrations of the potent synthetic halogenated greenhouse gases, like CFC-12, have risen from zero to hundreds of ppt (parts per trillion) concentrations. For example, CFC-12 has risen from zero to 538 ppt. This rise is due to industrial activities and use of the compound as a coolant in refrigeration and air conditioning units. Another greenhouse gas, tropospheric ozone (O_3) (not to be confused with stratospheric ozone), is formed from reaction of anthropogenic sources of nitrogen oxides and volatile organic compounds in the atmosphere derived from the burning of fossil fuels and biomass. The 1987 Montreal Protocol and its amendments have had a significant effect on slowing the rise of the chlorofluorocarbons in the atmosphere, but other halogenated compounds that have replaced the chlorofluorocarbons are rising in concentration in the atmosphere. With the well-documented rise in the concentrations of the greenhouse gases in the atmosphere, one would anticipate an increase in global temperatures. In addition, the anthropogenic greenhouse gases persist in the atmosphere for years to decades to centuries implying impacts on the climate far into the future.

Natural and anthropogenic micrometer-sized aerosol particles in the atmosphere also affect climate directly or indirectly. In general, the aerosols in the lower atmosphere are removed on time scales of days to weeks and their climatic impacts are mainly that of cooling, particularly on a regional scale. The most notable of the aerosol compounds is that of sulfate (SO_4) aerosol which may affect climate directly by reflecting sunlight back toward space or indirectly by acting as cloud condensation nuclei (CCN) and leading to cloud formation, the type and distribution of which affect climate. For example, the eruption of Mt. Pinatubo in the Philippines in 1991 that spewed sulfur compounds high into the upper atmosphere led to a cooling of the planet on a time scale of several years of about 0.5 ^oC. The burning of fossil fuels, particularly coal, generates sulfur gases that in the atmosphere are converted to sulfate aerosols and the cooling and cloud formation effects of these particles are considered in present climate models.

Global dimming is the gradual reduction in the amount of direct solar irradiance at the Earth's surface that has been observed for several decades after the start of systematic measurements in the 1950s. It appears to be caused by air pollution and the increase in particulates such as sulfur aerosols in the atmosphere due to human activities. The effect varies geographically. Worldwide it has been estimated to have resulted in a 4% reduction in irradiance between 1960 and 1990. The trend appears to have been reversed during the past decade, as the lower atmosphere has become less polluted in some regions. The dimming has affected the water cycle by reducing evaporation and likely was the cause of droughts in some areas. Dimming also creates a cooling effect that may have partially masked the enhanced greenhouse effect.

The sun’s output of solar energy also affects climate. In actual fact, during the past four billion years, the sun’s luminosity has increased about 30%. More germane to the present global warming issue is that during periods of high sunspot activity, the Earth receives slightly more solar radiation at the top of Earth’s atmosphere; the converse is true at times of low sunspot activity. The cool period of the Little Ice Age of 1350-1850 was probably due in part to a decrease in the amount of solar radiation received from the sun at the top of the Earth’s atmosphere However, for the period 1750 to 2005, it appears that the sun’s forcing on climate has only been about + 0.12 (0.06-0.30) W m^{-2} out of the total net anthropogenic forcing of +1.6 (0.6-2.4) W m^{-2}. The global average radiative forcings on climate of the various major factors involved in climate change from 1750-2005 are shown in Figure 1.

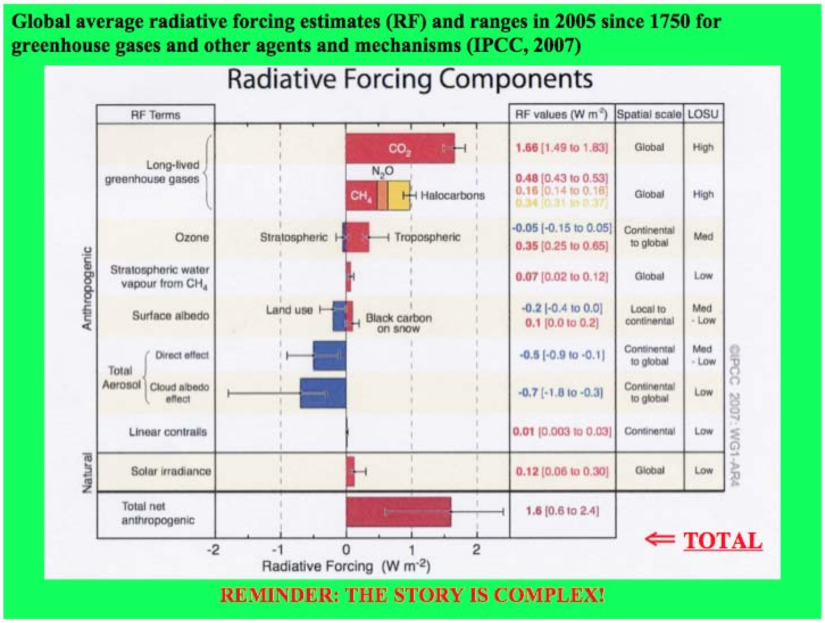


Figure 1. Global average radiative forcing estimates (RF) and ranges in 2005 since 1750 for greenhouse gases and other agents and mechanisms (IPCC, 2007).

The first report of the IPCC in 1990 suggested that the warming of 0.3 ^{o}C to 0.6 ^{o}C during the twentieth century was reasonably consistent with projections from the climate models in operation at the time but also within the ballpark of natural climate variability. The attribution of the warming to human or natural causes was not definitive at that time. By 2007, the IPCC stated that there is a *very high confidence* that "the global average net effect of human activities from 1750 to 2005 has been one of warming, with a radiative forcing of +1.6 (0.6-2.4) W m^{-2}". This climatic forcing has led to a nearly 1 ^{o}C rise in temperature since 1750. This temperature change is remarkably close to that predicted for a climate system that has a climate sensitivity response to increasing greenhouse gas concentrations of 2-3 ^{o}C (best climate sensitivity estimate is 2.8 ^{o}C) for a doubling of effective atmospheric carbon dioxide concentration over its 1850's concentration of 280 ppm. In addition, the IPCC concluded that the probability that the warming is caused by natural climatic processes alone is less than 5%. Most (>50%) of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely (confidence level >90%) due to the observed increase in anthropogenic greenhouse concentrations (IPCC, 2007).

Recent Findings Relevant to Global Warming

We should bear in mind in the material discussed in later sections that the IPCC has a very rigorous review process. However, research was excluded from the 2007 document if it were controversial, not fully quantified, or not yet incorporated into models. Furthermore, no papers published after 2005 could be discussed in the report.

Positive feedbacks to the rate of atmospheric greenhouse gas accumulations and climate and "tipping points" (a point at which the climate system and biogeochemistry suddenly switch from one mode to another) were not always included in the IPCC 2007 chapter discussions. Of importance are the post-2005 observations that:

1. Land and ocean surface temperatures have risen relatively rapidly in the early twenty-first century (Figure 2). Ocean temperatures down to 3000 meters are also on the rise.
2. Current climate models assume that ice sheets will melt slowly in response to increased warmth. Recent work shows that ice sheets fracture as they melt, allowing water to penetrate rapidly toward the bottom of the sheet with the result that the ice sheet surges and breaks up. The rate of ice loss in Greenland has more than tripled in this century (Velicogna and Wahr, 2006) and there has been rapid loss of sea ice around Antarctica and mass loss of ice in West Antarctica. If the Greenland ice sheet melted completely, this would lead to a 6-7 meter rise in sea level. The Larsen B ice shelf collapsed in 2005. The melting of the West Antarctic ice sheet would add 5-6 meters of sea level rise.

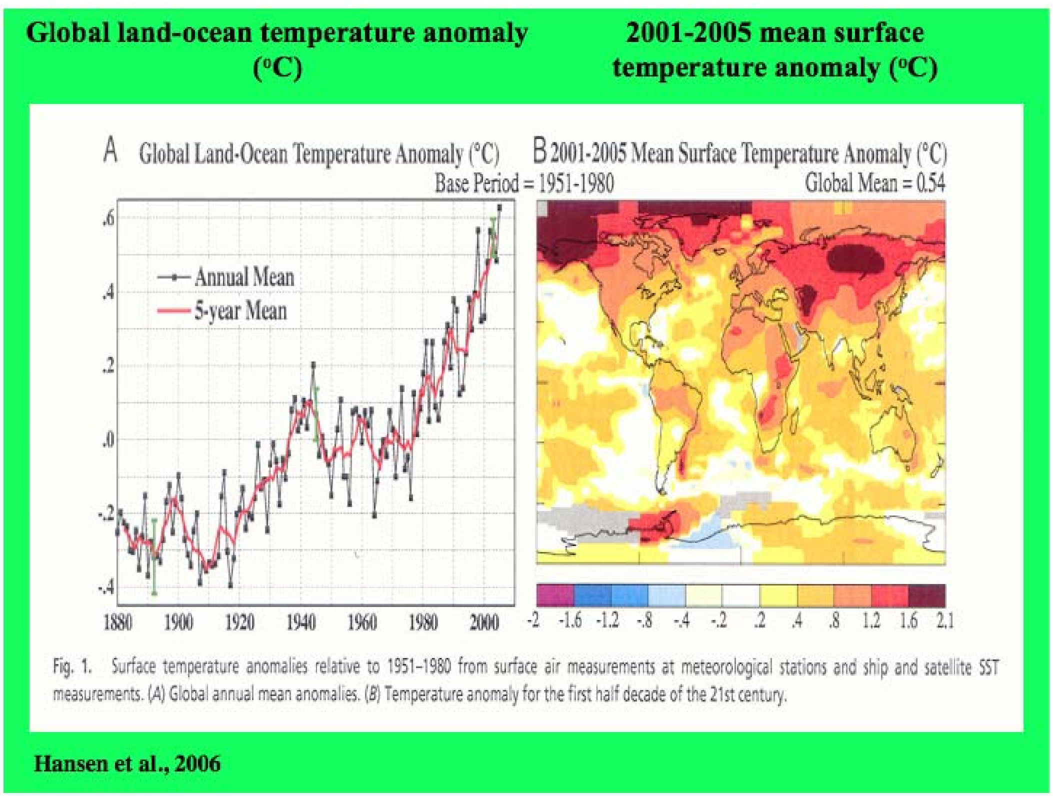


Figure 2. Global land-ocean anomaly for 1880 to 2005 and the 2001-2005 mean surface temperature anomaly. In just the latter period of time, the anomaly was 0.54 °C and of more importance is the fact that the anomaly over the high latitude of the Northern Hemisphere was up to 2.1 °C. It is this abnormal heating that is the cause of the warming at high latitudes of surface seawater and the melting of the Greenland ice sheet and the permafrost.

3. Global sea level is rising about 50% faster in the early twenty-first century than predicted by the IPCC in their 2001 report, perhaps the first sign of accelerated sea level rise. Average rates of sea level rise during the last several decades were about 1.8±0.5 mm/yr, with a larger rate of increase during the most recent decade of 3.1±0.7 mm/yr. However, the IPCC 2007 report in their worse case scenario for global sea level rise reduced their sea level rise estimates from 88 to 59 centimeters for the period 2000 to 2100, but the new observational findings of this century were not incorporated in the models used in the IPCC 2007 report.
4. It appears that the Gulf Stream has slowed about 30% during the period 1957-2004. This is a crucial current in terms of transporting heat to high latitudes in the North Atlantic and its slowing would have major climatic implications and is a key aspect of models of past climatic change and tipping points.
5. The positive feedback of the effect of rising temperatures on the release of carbon dioxide and methane from soils, permafrost, and the seabed were not considered in detail in the 2007 IPCC report. The permafrost is melting rapidly in western Canada and Siberia. Indeed, standing bodies of water are forming in the Siberian permafrost with high methane concentrations.
6. Arctic sea ice area has decreased about 15% since October 2005 (Nghiem et al., 2006) and in 2007 there was a record decrease in the area of sea ice and the Northwest Passage was opened for the first time in centuries.
7. Higher rates of precipitation are now observed at mid to high latitudes and lower rates in the tropics and subtropics, with corresponding changes in surface seawater salinities.
8. The North Pacific region of relatively low productivity and nutrient deficient surface waters has expanded to the east as the surface ocean has warmed with poorly known consequences for pelagic fishes, like tuna.
9. Ocean surface water pH has fallen 0.1 pH unit ("ocean acidification") (Orr et al., 2005; Andersson et al., 2005) (the pH scale is logarithmic so this represents a significant increase in hydrogen ion concentration) since 1700, and the projected rate of change in ocean surface water pH will increase on into this century and beyond unless anthropogenic emissions of carbon dioxide to the atmosphere are curtailed. Invasion of carbon dioxide into the deeper ocean has resulted in the shoaling of the depth at which the calcareous skeletons of sinking pelagic organisms can be dissolved (Feely et al., 2004).
10. In certain regions of the oceans, the strength of the oceanic sink of anthropogenic carbon dioxide is weakening as the partial pressure difference of carbon dioxide between the atmosphere and the ocean decreases.

The Pacific Region Temperature, Precipitation, Sea Level and Storm Projections

Regional projections of climate change variables on into this century, based mainly on climate models, although much improved, are still not as robust as global projections. Large deviations among models make regional estimates across the Pacific region uncertain. However, the following diagrams show the temperature, precipitation, and sea level projections for this century for the Pacific region based on the United

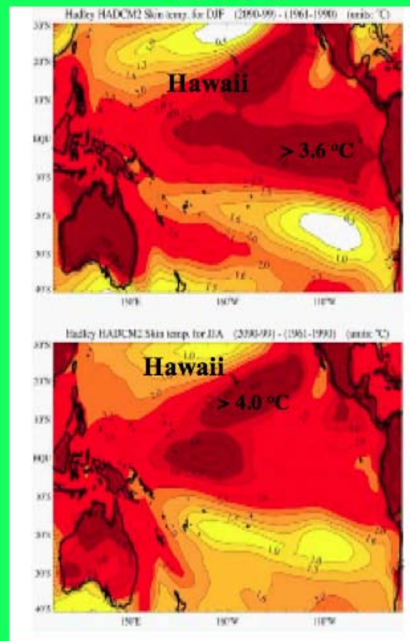
Kingdom's Hadley Centre for Climate Prediction and Research HADCM2 General Circulation Model (GCM). Notice that Australia and the Pacific tropics and subtropics are very likely to warm the most, with temperatures in Hawai‘i in the late twenty-first century being 2-3 ^{o}C higher than at the beginning of this century. There are likely to be strong seasonal and geographical changes in temperature for the Pacific region induced by global warming.

Annual rainfall is likely to increase in the equatorial belt of the Pacific on into this century and likely to decrease over southwestern Pacific islands, with Hawai‘i perhaps being wetter or drier. The latter is more likely. Whether Hawai‘i is wetter or drier in a globally warmer word is mainly a function of the behavior of the trade wind inversion above which rainfall decreases sharply.

Sea level using the HADCM2 GCM is projected around Hawai‘i to be about 40 centimeters higher in the late twenty-first century than at the beginning of this century. However, the HADCM2 model projections do not include the melting of the ice sheets, and it is likely because of ice sheet melting, warming of surface waters, and acceleration of the melting of valley and mountain glaciers that global mean sea level could reach a level one meter higher than in the year 2000 by the end of the twenty-first century. As with precipitation, the rise in sea level is not likely to be uniform throughout the Pacific region but geographically variable making regional estimates uncertain. Notice, however, that with a one-meter rise in sea level, areas like Waikīkī in O□ahu, Hawai‘i (a high Pacific island) will be drowned. New marshes would be formed and salt water during storms with inordinate daily high sea levels would be prevalent in sewer drains and an important component of the flooding. Beach erosion would intensify and the distribution of beach sand about the Hawaiian Islands would change. Homes close to the present shoreline would be more susceptible to flooding, erosion and damage. For low-lying Pacific islands like Majuro in the Republic of the Marshall Islands, a one-meter rise in sea level would have devastating consequences. For example, for the Laura atoll region of the Marshall Islands, the shoreline would retreat by about 150 meters on each coast, which would result in a loss of more than 25% of the atoll's surface area. In addition, approximately 50% of the volume of Laura's freshwater lens would be salted out and unusable as a fresh water resource (Miller and Mackenzie, 1988; Holthus et al., 1992). The damage due to storms and resulting surges would be amplified considerably by the rise in sea level.

There is still considerable uncertainty concerning how storm and hurricane frequency and intensity will change for the Pacific region in a warmer world. Multi-model ensembles do not give a clear picture of how storminess in the Pacific region will be affected by temperature and hydrologic changes. It is likely with global warming that the warm water (Pacific warm water pool) and intense atmospheric convection that are normally confined to the western equatorial Pacific will move eastward into regions that presently only experience warm waters during El Nino events. In part as a result of this, the HADCM2 model projects increased storminess in the Hawaiian Islands as well the Federated States of Micronesia and the Republic of the Marshall Islands. Storminess is projected to decrease for the Pacific region that includes Fiji and the French Polynesian Islands. It should be kept in mind that these findings are not as robust as we would like, but we do know that the patterns of storms will change in the Pacific region due to global warming.

ΔT in °C



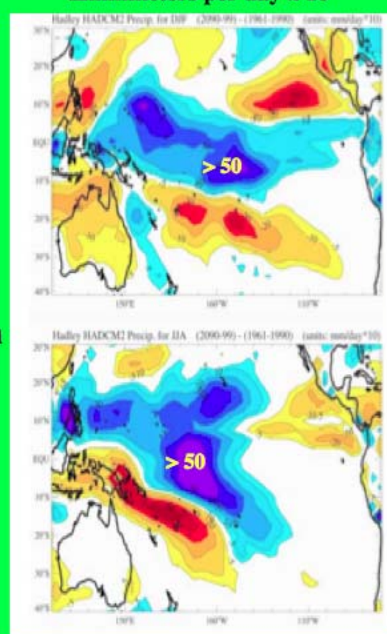
Winter

Summer

Pacific region surface temperature changes between the end of the 20th century and the end of the 21st century: Hawaii 2-3 °C warmer

Shea et al., in Guidry and Mackenzie, 2006: Hadley HADCM2 model

Δmillimeters per day x 10

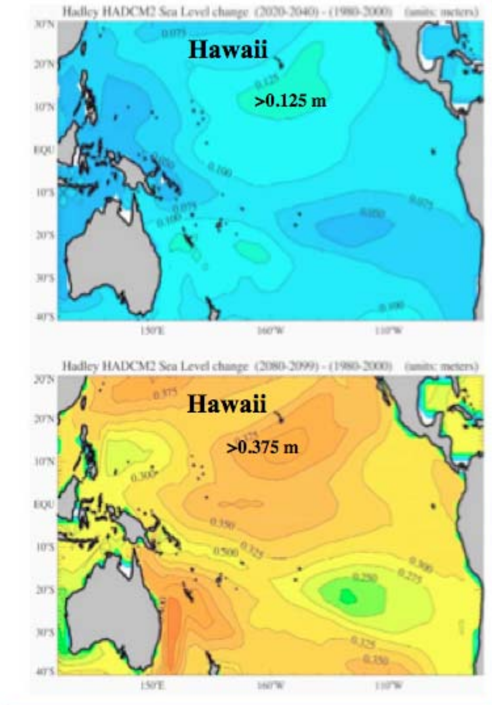


Winter

Summer

Pacific region precipitation changes between the end of the 20th century and the end of the 21st century: Hawaii perhaps wetter, perhaps drier (mainly a function of elevation of trade wind inversion above which rainfall decreases sharply)

Shea et al., in Guidry and Mackenzie, 2006: Hadley HDCM2 model



Pacific Region Projections of Sea Level Rise in Meters

Late 20th to mid-21st century

Late 20th to late 21st century

Shea et al., in Guidry and Mackenzie, 2006: Hadley HDCM2 model

Drowning of Hawaii: the effect of a one meter (39 inches) rise in sea level on Waikiki and environs

(Courtesy Chip Fletcher, University of Hawaii Research Group)

Need to prepare for the possibility of a one meter rise in sea level by 2001

Ocean Acidification

The modern environmental problem of ocean acidification due to emissions of carbon dioxide to the atmosphere because of fossil fuel combustion and land-use changes and their partial absorption in surface ocean waters has been discussed in the literature since at least the early 1970s (Broecker et al., 1972). More recently the observational record of surface ocean water pH and model calculations show that surface water pH has declined about 0.1 pH unit since the 18th century (Caldeira, et al., 2005; Orr et al., 2005; Andersson, et al., 2005). Accompanying this decline in pH is a decline in the carbonate saturation state of the world's surface ocean waters with respect to all carbonate minerals. Model calculations show that under a Business as Usual emissions scenario (Intergovernmental Panel on Climate Change IS92a), surface water pH could reach 7.85 by the year 2100 accompanied by a 30% decrease in carbonate saturation state (Figure 3). Such a decrease would very likely affect the calcification rates of both benthic calcifying organisms, like corals and coralline algae, and pelagic calcifiers, such as foraminifera, pteropods, and Coccolithophoridae, accompanied by other major changes in marine ecosystem communities, structure and recruitment. Coastal ocean acidification will be especially detrimental to the coral reefs of Hawai'i and the rest of the Pacific region. *The only way this problem can be alleviated is by reduction of anthropogenic carbon dioxide emissions to the atmosphere.*

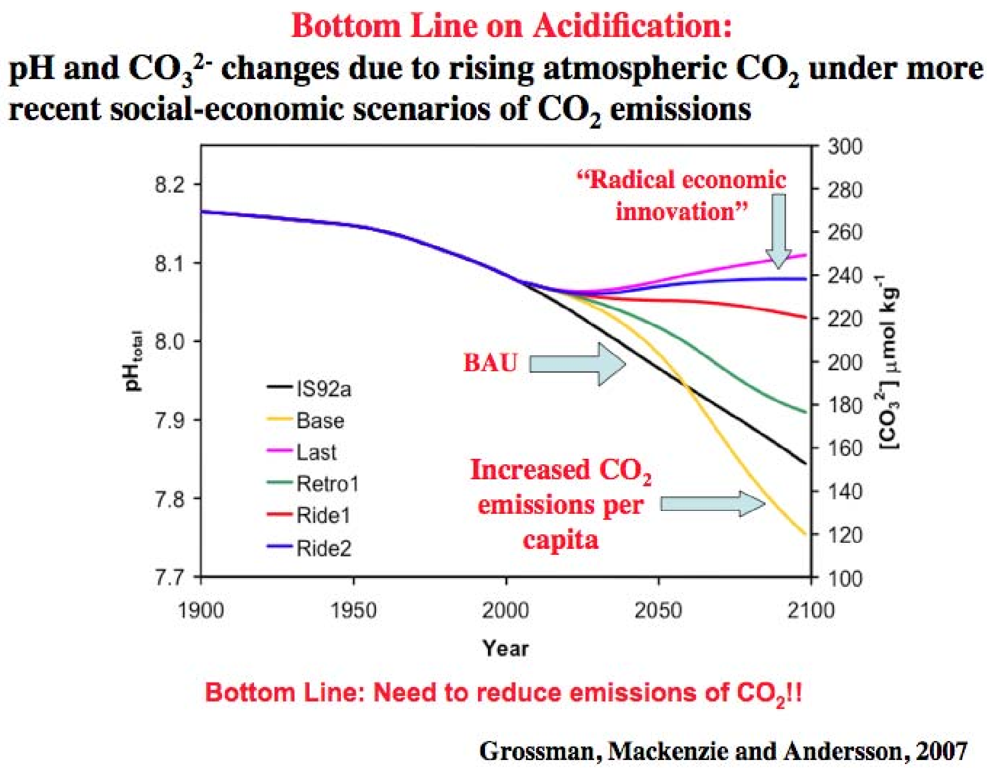


Figure 3. pH and carbonate ion concentrations, a measure of carbonate saturation state, as predicted under various greenhouse gas emissions scenarios. Only radical economic innovation measures will prevent the oceans from becoming more acidic.

Conclusions and Recommendations

Future global climate change and the resultant impacts to water resources are very serious problems for Pacific island communities. For small low-lying island communities like Majuro and large volcanic islands like the southern Hawaiian Islands, water is a most precious natural resource. Majuro and Hawaiʻi represent the end points for two different types of Pacific island communities. Majuro in the Republic of the Marshall Islands is a small low-lying atoll two to three meters above sea level. The impact of projected sea level rise on Majuro's water resources is potentially severe. The low-lying atoll lacks groundwater resources for its freshwater needs and relies primarily on rainwater catchment systems for freshwater supply. The groundwater reservoir does provide a freshwater source for times when rainfall is low and thus rainfall catchment is reduced. Rising sea level, exacerbated by storm activities, all due to climate change, will reduce Majuro's volume of fresh groundwater and that of other low-lying Pacific islands. In addition to climate change, rising population will place additional pressures on the groundwater resource. To undertake shoreline protection measures for low-lying Pacific islands is costly but will be necessary to protect its groundwater and land area resources from rising sea level and storm events. Desalinization is another measure that could be implemented to support, at least in part, present and future freshwater needs of both high- and low-lying Pacific islands, albeit at considerable cost.

Compared to the low-lying atolls and island communities like Majuro, the island of Oʻahu is a relatively large volcanic island with a peak elevation of over 1200 meters (3,936 feet) and a much larger groundwater resource. This groundwater resource already supplies Oʻahu with 92% of freshwater use. The development and use of the groundwater system have reached the point where the sustainability of current and future water usage rates is in doubt. Even if future climate change were to lead to increased precipitation for Oʻahu, the elevated temperature, via its influence on evaporation rate, could result in a reduction in groundwater recharge rates and thus a decrease in the groundwater reservoir size. Add to this the increased groundwater usage due to population growth and also the background of future sea level rise and Oʻahu's groundwater resource could be significantly taxed. The future rise in sea level could also threaten the economy of Hawaiʻi by negatively impacting vital areas (e.g., airport runway and Waikīkī) in close proximity to shorelines. The rise in sea level could also result in the flow of salt water from the ocean to land via the storm drainage system that during storm events can result in flood damage to areas such as the Mapunapuna industrial district.

A summary of the some key concerns and needs for Hawaiʻi and Pacific island communities follows:

- The adaptive capability of the human systems is generally low for small islands and their vulnerability is high; small island communities are likely to be among those regions most seriously impacted by climate change.

- The projected global sea level rise and its geographical variability in this century will cause enhanced coastal erosion, loss of land and property, dislocation of people, increase risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes.

- Islands with very limited water supplies are highly vulnerable to the impacts of climate change on their water balance.

- Coral reefs are likely to be negatively affected by bleaching due to increasing temperature and by reduced calcification rates due to higher carbon dioxide levels and consequent ocean acidification; mangroves, sea grass beds, and other coastal ecosystems and their associated biodiversity are likely to be adversely affected by rising temperatures, accelerated sea level rise, and increasing acidity of seawater.

- Declines in the water quality and pH and increasing temperatures of coastal ecosystems could negatively impact reef fish and threaten reef fisheries, those who earn their livelihoods from reef fisheries, and those who rely on the fisheries as a significant food source.

- Limited arable land and soil salinization make agricultural practices for small islands, both for domestic food production and cash crop exports, highly vulnerable to climate change.

- Tourism, an important source of income and foreign exchange for many islands, likely would face severe disruption from climate change and sea level rise.

- Island communities will mainly have to adapt to climate change and its impacts. Mitigation of greenhouse gas emissions is important from a strategic and sustainability viewpoint but will have little effect on rising atmospheric greenhouse gas concentrations.

- There is a need for a new Pacific regional assessment of climate variability and change in light of improved models and observations made since the last assessment of 2001.

- Regional-based climate information services should be established for the Pacific region, perhaps by the University of Hawai‘i or by NOAA, to provide climate services that bridge the gap between local weather and global climate change information for island communities. These services should include community educational resources on climate change and variability and on the anticipated impacts and vulnerability and adaptation to climate change and rising sea level.

Thank you for giving me the opportunity to address the Committee. I look forward to answering your questions.

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